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REDUCTION OF THE LOADING EFFECTS OF FISH FARMING – A LITERATURE REVIEW

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1. GENERAL

Much attention has been paid lately to the loading effect of fish farms on waters. There is a general trend towards reducing the load, especially that caused by phosphorus. Therefore, testing and development of different wastewater treatment methods have been carried out at fish farms. Initiatives have been made to find more comprehensive means of reducing the load by considering the entire establishment and its operation. This has resulted i.a. in the development of new types of farms, rearing structures, and feeds (Kera 1983). The creation of efficient wastewater treatment methods has been limited by **the very large quantities of water** involved (the biggest farms use several m^3 per second) and **the very low contents of contaminants in the wastewater** (clearly lower than e.g. in municipal wastewaters) (Parjala et al. 1984 b). The present article evaluates, primarily on the basis of the literature, the applicability of the different methods for reducing the loading effect of fish farming.

2. SEDIMENTATION

In view of cost/benefit considerations, sedimentation has been regarded as the most advantageous and realistic method for treating wastewaters from fish farms (Warrer-Hansen 1982).

However, in establishments with earthen ponds and channels, sedimentation leads to the problem that the rearing ponds themselves act as settling basins on the bottom of which the sludge accumulates. It is true that the sludge gradually becomes suspended in the water again, but when the suspended solids reach the settling basin at the end of the installation, they are as a rule so poorly settleable, that only a very small portion of the solids are retained in the settling basin.

The following is an example of solids removal from a traditional earth pond and a circular self-cleaning rearing tank (Warrer-Hansen 1982) :

	3 min	6 min	11 min	15 min	30 min
Earthen pond	14 %	21 %	29 %	37 %	37 %
Circular self-cleaning tank	30 %	59 %	63 %	66 %	73 %

The following example illustrates also the efficiency of solid matter separation in earthern pond and circular self-cleaning tank, for different feed types (Warrer-Hansen 1982) :

	Retention time in settling basin	fresh feed	half-dry feed	dry feed
Earthen pond + settling basin	15 min	12 %	19 %	37 %
	30 min	15 %	31 %	37 %
Circular tank + settling basin	5 min	-	51 %	59 %
	15 min	-	57 %	66 %
	30 min	-	67 %	72 %

Thus, a **circular rearing tank** is obviously superior to an earthen pond in view of solid matter removal. However, according to the present consensus, large fish ($>$100 g) can not be reared in circular tanks successfully (Jaakkola 1981).

If self-cleaning rearing tanks can be used (as fry farms use them right now), a settling basin alone will give good treatment results with regard to the removal of solid matter and BOD_7 and fairly good results with regard to the removal of nutrients as well (Liao 1970).

The structure and the design of the settling basin have been discussed i.a. by Warrer-Hansen (1982). In view of the theory of surface load, the design flow rate has to be reduced by a factor of 1.5 to eliminate turbulence. The theory of surface load implies that the depth of the basin would not be important for the treatment efficiency of the basin. On the other hand, the flow in the basin should not exceed 2 - 4 cm/s, which may set certain limits for the basin depth and retention time as well.

A horizontal settling basin is expected to fulfil the following requirements : Width / length = 1/3 - 1/7, depth = 1.5 - 2.5 m, surface load $\leq$ 1.5 - 1.0 m/h, retention time $\geq$ 1.0 - 1.5 h, and Re-number $\leq$ 10 000.
The settling velocity of a particle just retained in a basin is roughly obtained from the ratio of flow rate Q (m^3/s) to basin surface A (m^2), that is, Q/A.

Figures 1 and 2 illustrate the significance of solid matter removal for reduction of the other load parameters and the relation between removal percentage and retention time of solids in different types of rearing enclosures.

According to Muir (1982), the required total volume V_t (L) of a settling basin is obtained by means of quantity of fish S (kg) at the farm, fish density in relation to flow rate P_f (kg of fish /L H_2O / min), basin retention time Θ (min), and volume coefficients k_i and k_o of the inlet and outlet zones of the basin :

$$V_t = (S\Theta / P_f) (L + k_i + k_o).$$

The required basin retention time can be estimated on the basis of the settling velocity of solids. The volume coefficients can be estimated on the ground that in general, 1 - 5 % additional space is needed for basin inlet and outlet zones to regulate the flow.

If a farm's water is aerated, the ratio of fish density to flow rate can be increased and the required basin volume decreased. For example, if P_f is doubled, V_t is reduced by half. On the other hand, part of the solids may become diffused, which means that basin retention time Θ must be correspondingly lengthened.

If lamellate basins are used for settling, which means that the settling area grows by factor F_a, the following is obtained :

$$V_t = (S\Theta / P_f F_a) (L + k_i + k_o)$$

E.g., if F_a = 10 (10 lamellae), the area required is reduced to 1/10.

If solids can be collected in the main flow to a certain spot, from where they can be removed by means of a secondary flow, the situation can be described by means of concentration factor F_c. If it is assumed that the secondary flow catches all solids from the wastewater of the farm, the following expression can be used :

$$V_t = (S\Theta F_c / P_f) (L + k_i + k_o)$$

If the secondary flow is 10 % of the main flow, F_c = 0.1. If the secondary flow does not catch all solids, the basin retention time must be increased and the treatment expanded.

It is to be noted that the first stage of solids removal does not much depend on the solids content. However, the removal of soluble substances depends on the content in accordance with the order of reaction, which means that the area, volume, etc. required by the treatment increases with decreasing content.

It is questionable whether settling basins should be built in fish farms with long retention times (several hours). The efficiency of the treament would typically be: solids 10 - 15 %, total phosphorus 0 - 20 %, total nitrogen 0 - 30 %, phosphate-P 0 - 20 %, and BOD 0 - 25 % (i.a. Kekkonen 1982, Selanne et al. 1983, Parjala and Tamminen 1984).

Fish farms use a large variety of settling and sedimentation basins. The simplest of them are mere earth-bottom ponds. The **hydroclone** is a recent application characterized by a small area (about 1/10 of the area required by traditional sedimentation basins) and large surface load. However, the hydroclone is suited only for rapidly settling solids (velocity of settling over 0.5 - 0.6 cm/s)(Parjala and Tamminen 1984).

The traditional horizontal and vertical settling basins would obviously remove more efficiently light-weight solids with a small particle size, but they are expensive and require a large area (Mashauri 1981).

3. FILTRATION

3.1 Peat filtration

The filter capacity of peat is based on :

- mechanical filtration
- biological filtration
- surface activity (adsorption)
- cation exchange

- water-retention capacity
- evaporation.

The dimensions of a peat filter are decided primarily by the filter structure, the capacity of the peat to retain contaminants, and the water permeability of the peat. Below are some general instructions concerning peat filter construction (Selanne et al. 1983) :

1) peat layer thickness must be 30 - 50 cm
2) peat layer must lay on drainage gravel and underdrains
3) sludge water must be conducted to the filter evenly by means of a distributor disc or a feeding plate
4) peat must be compacted by wetting it uniformly so that the filter develops no shortcuts and that it does not float
5) basin has to have earth walls so that when the peat dries, no cracks will form at the edge to allow shortcuts
6) filter has to have sufficiently high edges to prevent overflow
7) it must be possible to monitor the quality of the filter water
8) underdrains must have enough inclination to prevent clogging.

According to Selanne et al.(1983), the **preliminary design value** can be set at **200 g total phosphorus / m^3 peat.**

The following treatment results have been obtained in different tests (Selanne 1982, Selanne et al. 1983) :

solids	40 - 99 %
BOD_7	62 - 91 %
Tot. N	60 - 96 %
Tot. P	52 - 96 %
PO_4-P	39 - 97 %

The retention capacity of peat filters is primarily determined by **peat species, degree of peat humification,** and the **physical and chemical properties** of the peat. The **cation exchange capacity** of Finnish peat is generally 50 - 150 me/100 g, while its **water permeability** is 10^{-8} - 10^{-2} cm/s (Seppanen et al. 1982).

No large-scale practical experience with peat filtration exists at present. As it is, the method is applicable primarily to small farms only because

of the limited retention capacity and water permeability of peat. However, peat filtration is a suitable method for further processing and treating/ condensing sludge water pumped from sedimentation basins.

3.2 Mechanical fine filtration

The USA has used, besides the hydroclone, also mechanical fine filtration for solids removal from wastewater. Its costs are slightly higher than those of the hydroclone, and the scope of its application is the same as that of the hydroclone as far as flow rate is concerned.

As a rule, the mechanical fine filter, or micro-filter, consists of a cylinder covered with filter cloth or stainless steel screen with holes of a size of 20 - 120 µm. Microfilters are either horizontally or vertically rotating. The cylinder is cleaned by backwash which can be continuous or intermittent. In field tests carried out by Drehwing et al. (1979), these filters obtained efficiencies of 32 - 58 %, while the cleaning efficiency of the hydroclone under similar conditions was 18 - 55 %. Norway has experimented preliminarily with different cylindrical filters (mesh size 0.20 mm) in fry farms, obtaining efficiencies of 40 - 60 % (Lygren et al. 1983).

3.3 Sand filtration

Small farms may find it possible to use coarse sand filtration, even though the filter area would be large and the washing of the filter could be troublesome. Big farms and farms with recirculating water could install **continuous sand filters**, which need no backwash. These filters could be combined with chemical precipitation, without a need for separate basins for flocculation and sedimentation.

4. WASTEWATER LAGOONS

If a fish farm has lots of space at its disposal, it can treat its wastewater by means of wastewater lagoons, where the water is treated biologically and mechanically (sedimentation). However, the lagoons would have to be so large that the lagoon retention time, in view of the Finnish conditions (low water temperature) and the degree of dilution of the wastewater, would be several days (Liao 1979, Buhr and Miller 1983). Also, the lagoon should preferably

be no deeper than 40 - 50 cm. In practice, this system would require **aerator-equipped channels with continuously circulating water.** In an optimum case, the use of lagoons could yield a removal efficiency of over 60 % for BOD and solids, nutrients could be removed rather efficiently as well. The lagoons could **function poorly in the winter,** but on the other hand, the winter load would be small too.

Wastewater lagoons combined with sand filtration could constitute a suitable solution for **small farms.** A 1-m, coarse sand filter could obtain removal rates of 0.1 - 0.5 kg BOD/m^2/day and a lagoon correspondingly 0.02 kg BOD/m^2/day (Muir 1982).

Sand filter volume V_f can be calculated from

$$V_f = SXK_f/L_f$$

where L_f = load factor (e.g. 0.1 - 0.5)
S = fish mass
X = production of BOD
K_f = concentration factor (equivalent with reaction rate).

Correspondingly, volume V_l required by the lagoon is obtained from

$$V_l = SXK_l/L_l$$

where L_l = load factor (e.g.0.02).

In Finland, wastewater lagoons are associated with problems caused by the **unfavorable temperature conditions**, and also, when the wastewater to be treated is highly diluted, the retention times and lagoon areas required may become unrealistically large (Buhr and Miller 1983, Middlebrooks and Pano 1983, Uhlmann et al. 1983).

5. RECIRCULATION PLANTS

A good way to solve the environmental problems caused by fish farming is to install a recirculation system, which practically eliminates the load on waters. A recirculation plant means, however, that the farm contains several water treatment processes that are precisely planned and regulated.

The treatment of the water recirculated in these plants includes as a rule **removal of organic substances** e.g. by sedimentation, flotation, or sludge activation methods, a **biological filter** for nitrification-denitrification of nitrogen compounds, a **mechanical filter** (e.g. fast sand filter, pressure filter, zeolite filter) , **sterilization of water** by UV light, and possibly **temperature regulation** as well. The amount of fresh water needed for recirculation is usually a few % of the total amount of water.

Recirculation plants are discussed in greater detail i.a. by Hagebro et al. (1983), Hodal (1983) and Jernelov et al. (1980).

6. COAGULATION

In principle, the solids and the phosphorus contained in the wastewater can be removed by coagulation as well. However, the use of coagulation is limited because of the large water quantities and the low phosphorus and solids content. The cost of the coagulation chemicals would be relatively high. Also, the coagulation basin must be relatively large (unless supplementary continuous sand filters are used), because the period of interaction between the coagulation chemical and the matter to be coagulated must be long, due to the low content.

It is possible to use coagulation in a supplementary manner to **increase the settling velocity of solids in sedimentation units** and also to **concetrate sludge water**. This kind of application has been tried, but no large-scale experiments have been carried out, and experience is lacking.

The coagulation chemicals to be used would be primarily $FeSO_4$, $FeCl_3$, $Al(S)_4)_3$, $Ca(OH)_2$, CaO and polyelectrolytes. Favorable results have been obtained i.a. in preliminary trials performed at the Laukaa Central Fish Farming Plant (Selanne 1982, Selanne et al. 1983). However, no trials have been carried out on a practical scale and under practical conditions.

The possible uses of coagulation at fish farms have been discussed also by Makinen and Naukkarinen (1982).

7. AERATION

Aeration is another method for treating wastewaters. Aeration and oxygenation are already practised at fish farms to some degree, to improve oxygen conditions in rearing ponds and thus to increase growth.

It has been proposed i.a. that aeration be carried out in a separate aeration basin at the end of a plant, where it could be combined with coagulation of phosphorus (Anon. 1980). It would be possible to combine aeration with settling as well. However, aeration carried out prior to sedimentation may, by breaking up the frail organic solid particles, **make the separation of poorly-settling solids more difficult.**

Aeration affects primarily the O_2, CO_2, NO_2 and NH_3 contents. By aeration, the **O_2 content can be made to rise** to its saturation value and the **CO_2 content can be made to decline.** Effective aeration makes **NH_3**, the most important nitrogen metabolism product of fish, **oxidize to NO_3**, which to some degree decreases the secondary oxygen consumption. Especially **in earthen ponds and earthen channels, efficient aeration can promote the dissolution of NO_2, NO_3 and NH_4 from sludge and solids** (Hollerman and Boyd 1980).

Research on aeration is still needed with regard to its economy, efficiency, and applicability in wastewater treatment. In any case, to be efficient, the **retention time** required by separate aeration would be **rather long** (several hours).
Heerfordt and Hodal (1983) studied the efficiencies of different aerator types under standard conditions, primarily in view of increasing fish pro - duction. The principles of aeration and different types of aerators have been discussed in greater detail by Hiidenheimo et al. (1983).

8. POSSIBILITIES OF REDUCING PHOSPHORUS LOAD

A reduction in the phosphorus content of feed from 1.5 % to 1.0 % implies a 45 % reduction in the phosphorus load to the water, provided that the other variables do not change. Correspondingly, a reduction of the feed coefficient from 1.5 to 1.0 decreases the phosphorus load to the water, calculated per kg of feed consumed, by 10 - 20 % and the phosphorus load per kg of fish produced by about 45 % (Makinen 1983).

Table 1 (Makinen 1983) shows an example of the importance of the phosphorus content of feed and of the feed coefficient for reducing the phosphorus load.

If it is estimated that half of the total phosphorus load is in the solids to be settled, the **total phosphorus removal efficiency depends decisively on the solids separation efficiency.** Even though all solids could be separated, which requires that the sludge is fresh (less than a week old), half of the total phosphorus would still remain. Under the most favorable conditions, 20 - 25 % of phosphorus load can be removed from old, decayed sludge.

Table 1 Example : a farm producing 100 t per year

Phosphorus content of fish	1.4 %	0.4 %
Phosphorus content of feed	1.5 %	1.0 %
Feed coefficient	2.0	1.5
Recovery of phosphorus as sludge	0 %	50 %
Annual phosphorus load to watercourse	2 600 kg	550 kg

Table 2 Phosphorus load per kg of feed, at different sludge removal efficiencies

Source	Feed	Phosphorus load g/kg of feed		
		Efficiency of sludge removal		
		0 %	50 %	100 %
Selanne et al. (1983)	T40	4.7	3.0	1.2
	T40	5.9	4.8	3.7
	Tess	5.1	3.8	2.4
	Forelli	6.7	5.4	4.1
Myllyla		10.8	8.3	5.8
Selin et al.	Test feed	5.7	4.1	2.9
	Control feed	9.7	7.1	4.4
Sumari et al.	Test feed	10.1	7.0	3.9
	Control feed	8.1	6.3	4.4

By a complete sludge removal, 30 - 80 % of phosphorus load could be removed (Makinen 1983).

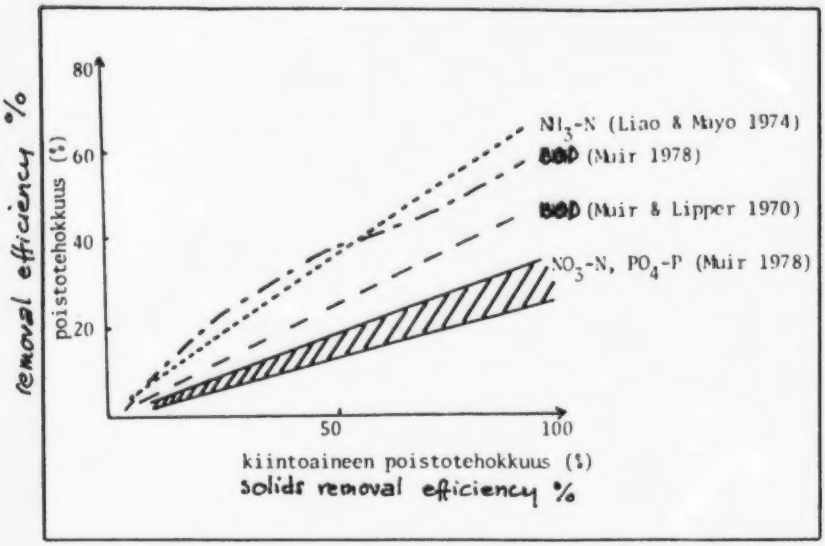

Fig. 1 Effect of solids removal efficiency on other load parameters (Muir 1982)

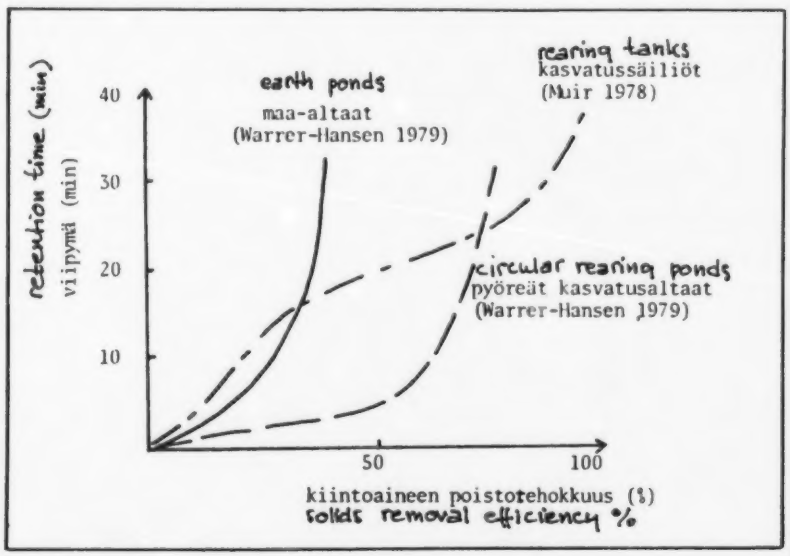

Fig. 2 Effect of retention time on solids removal efficiency (Muir 1982)

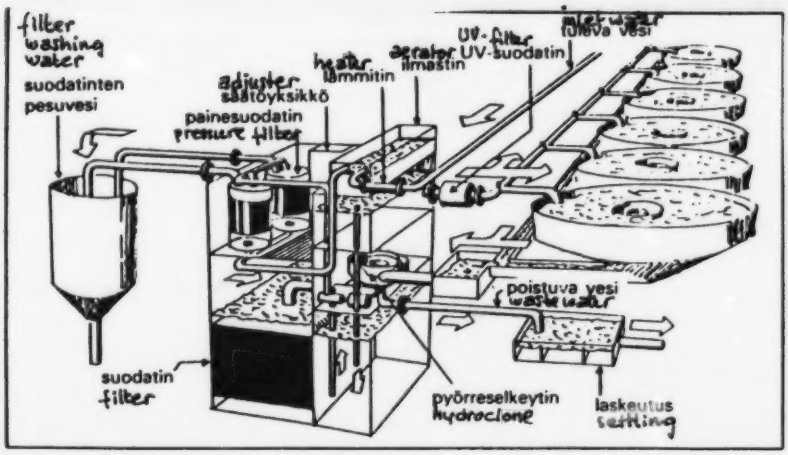

Fig. 3 Example of recirculation plant

Table 3 Relative capital costs of different basins (Muir 1982) :

Pond without embankment	1.0
Embankment pond	1.3
Brick, concrete, or metal pond or channel	1.2
Fibre glass tank	1.9
Filtration ponds	1.3 -1.6

If sludge removal is carried out to remove phosphorus, a decision has to be made with respect to the method to be used for wastewater treatment. Letting **sludgewater be absorbed in soil** is difficult, because an area of 1 m^2 would be required for 1.5 - 2.0 m^3 of sludgewater (solids content about 7 %). **Peat filters** could be used at small farms. In peat filtration, the maximum total phosphorus load per 1 m^3 peat is 200 g. It is probably most practical to **pump the produced sludgewater into tanks to which chemical coagulants are added** (e.g. 2 - 4 kg lime/m^3). The sludge is then allowed to **settle**, after which it is transferred to a **sludge bed to dry** (Makinen 1983).

9. REMOVAL OF NITROGEN COMPOUNDS

Zeolite filter ($NA_{12}((AlO_2)_{12}(SiO_2)_{12})$) , a method based on ion exchange, can be used to **remove** nitrogen compounds and especially **ammonia.** It functions, independently of temperature, in the pH range 4 - 8, and it is not affected by other substances like biological filters are (Anon. 1983). The specific gravity of zeolite is 0.69 and its price about Fmk 35/kg (Hiidenheimo et al. 1983).

Aeration (stripping) and nitrification can also be used to remove NH_3-N.

Removal of nitrogen compounds from the wastewaters of fish farms is not, however, of as much current interest as is the removal of phosphorus, except in recirculation plants.

10. BIOMASS FOR NUTRIENT REMOVAL

It has been proposed that the nutrients in wastewaters could be removed also by means of biomass, primarily by aquatic plants but also by means of the food chain plankton - benthic fauna - fish (Lindqvist et al. 1981, Puustinen and Lindqvist 1982, Hejkal et al. 1983).

Removal of nutrients by aquatic plants requires a **biomass basin** with a depth not exceeding 1 m, which can at the same time function as a settling basin. According to Lindqvist et al. (1981), the biomass basin of a medium-sized fish farm should have a minimum area of **4 000 - 10 000 m^2.**

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When plans are made to remove nutrients by means of plants, the following points have to be considered :

- plant species and their adaptability (plants with submerged or floating leaves tolerate harvesting best)
- capability of plants to take up nutrients from water
- production (kg/ha/year or kg/ha/day) and harvesting properties of plants
- easiness of propagation in the beginning of growth period
- water depth and flow velocity
- water retention time and interaction time with plant mass
- basin shape and degree of shadedness
- nutrient content and physical quality of basin bottom

The growth rate of the plants is affected primarily by nutrient ratios and quantities, plant density, amount of available solar radiation, and temperature. The critical N/P ratios and quantities that guarantee maximal production are not known for many plant species. For example, the optimum N/P takeup ratio is 3/1 - 5/1 for water hyacinth (**Eichornia crassipes (Mart.) Solms**) (Reddy and Sutton 1984). Plants are capable of using mainly only soluble nutrients in an inorganic form. Furthermore, many aquatic plants can remove nitrogen more efficiently than phosphorus (Reddy 1983). Thus, in many species the retention time needed for phosphorus removal is longer than that needed for nitrogen removal. Plants absorb primarily nitrogen in ammonia form but also nitrates and nitrites to some degree (Martin and Goff). Also, the optimum growing density of plants depends very much on the amount of available nutrients and the season. Maintenance of the optimum density throughout the growing period frequently requires a thinning of the vegetation during the time of the most rapid growth.

Aquatic plants attain their maximum growth rate as a rule at a temperature of 25 - 30 ^{o}C. When the temperature drops below 10 ^{o}C, the production of the plants decreases very rapidly to zero (Reddy and Sutton 1984). The low production at low temperatures is further emphasized, if the nutrient content of the water is poor.

An efficient nutrient removal by plants requires a retention time in the biomass basin of several days (5 - 20 d) even under favorable conditions. The retention time required is longer during seasons with low temperatures.

The size of the biomass basin is determined primarily by the quantity of the water to be treated, the retention time required, and the depth of the basin. In Finland, the water quantity to be treated during a summer would be perhaps 100 - 200 m^3/ha/d (Reddy and Sutton 1984).

It is to be noted that at the end of the growing season, the biomass has to be removed from the basin, so that the nutrients stored are not released from the wilted plant matter and the basin bottom during fall and winter.

It is obvious that the use of biomass for reducing nutrient loads is not an applicable method under the Finnish conditions, if used alone and in its present form, because of the low temperatures and the short growing season. The method is further impaired by the same factors as the conventional methods are affected by, namely low nutrient contents of water and large water quantities. However, little information or experience is available about the use of biomass for wastewater treatment in Finland, and therefore, it may very well be possible that the method can be adapted to use in Finland as well.

The use of a biomass basin has been studied preliminarily at a Finnish fish farm (Puustinen and Lindqvist 1982). Experiences of summer 1981 proved that in the most favorable case, a maximum of about 10 % of total phosphorus load and about 5 % of total nitrogen load were removed by aquatic vegetation (i.a. choke pondweed) in the settling basin (about 0.8 ha, estimated flow rate 1.0 - 1.5 m^3/s). However, the basin could retain nutrients only during mid-summer, while in late summer the effluent contained more bound phosphorus than the influent.

11. COSTS

Very little information exists on the costs of wastewater treatment at fish farms. These costs consist of the **costs of water treatment** and the **costs of the basins, structures, and equipment** required. The treatment costs depend decisively on the treatment unit and the treatment method. The basin costs are determined by the **basin size and material.** The capacity of the basin is also influenced by **fish density** per flow rate (kg/L/min) and volume (kg/m^3).

Muir (1982) estimated that at big fish farms, a 50 % increase in capital costs would achieve a solids removal rate of 30 - 40 % and a BOD removal rate of 20 % by single settling. In small farms, it would be possible to remove, by a 10 - 20 % capital cost increase, 10 - 20 % of solids and 5 - 15 % of BOD.

Different water protection methods and their annual costs have been discussed by Makinen (1983) as well.

12. CONCLUSIONS

On the whole, the **loading effect** of fish farms can be assumed to have **decreased** considerably e.g. from the 1970's, due to factors such as growing attention by the water authorities. It has been possible to reduce the load especially by **indirect measures** such as development of feeds and the feeding and farming technology. Also, water treatment and sludge collection methods have been developed. However, it is easier to essentially reduce the load in rearing ponds than at the end of a facility, by separate unit operations based on load quality and wastewater properties.

As the traditional **earthen pond and channel farms** will probably continue long to be the dominant farm types in Finland, efforts should be made particularly to **develop sludge separation methods** for these farm types. At the moment, preliminary work is carried out to develop different types of sludge collection pockets etc. However, not enough attention has been paid yet to the **hydraulics of the rearing pond and the behavior of solids and sludge on different interfaces.** Studies of sludge behavior and basin currents would help to develop simple, easily applicable solutions for collecting the sludge to certain locations in a basin, from where the sludge could be removed in a relatively easy and inexpensive manner.

Also, it has to be remembered that the treatment method to be chosen and its economy depend critically on the treatment efficiency required. Up to now, fish farming plants have been presented no demands mentioning figures concerning treatment efficiencies.

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* LKKVL possibly refers to the Laukaa Central Fish Farms (Translator's note)